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US Army Corps of Engineers

TECHNICAL REPORT HL-91-13

# SOIL CONSERVATION SERVICE LOW DROP STRUCTURE MODEL STUDY

## Hydraulic Model Investigation


by

Charles H. Tate, Jr.

Hydraulics Laboratory

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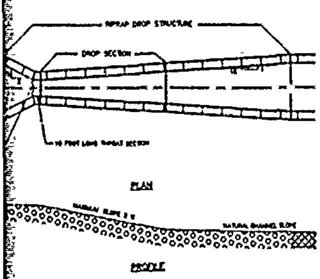

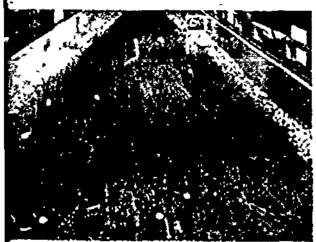

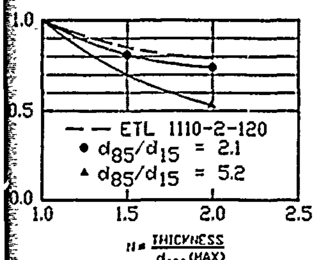




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**13. ABSTRACT** *(Maximum 200 words)*

The US Department of Agriculture Soil Conservation Service has been using loose riprap grade control structures based on the equal energy concept for several years with mixed success. Earlier model studies resulted in modifying the design criteria to include a 1:16-exit flare at the downstream end of the structure to return to the downstream channel width. That change resulted in a much longer structure with associated higher construction costs. This study developed a new design criteria for loose riprap drop structures that incorporates recent advances in riprap stability research, numerical backwater codes, and hydraulic model study results. The design method and tools presented herein allow the designer to optimize the size and amount of riprap used in the design.

**14. SUBJECT TERMS**

Drop structure
Grade control structure
Riprap drop structure
Riprap stability

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## PREFACE

The model investigation reported herein was authorized by the US Army Engineer District, Vicksburg, on 10 February 1988.

The studies were conducted during the period February 1988 to July 1989 in the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES), under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL, and R. A. Sager, Assistant Chief, HL; and under the general supervision of G. A. Pickering, Chief, Hydraulic Structures Division (HSD), HL, and J. F. George, Chief, Locks and Conduits Branch (LCB), HSD. Tests were conducted by Messrs. C. H. Tate, Jr., and J. Cessna, LCB, and the report was prepared by Mr. Tate.

The WASP2 computer program referenced in this report was developed by Messrs. Donald E. Twiss and David J. Sarvary, California Soil Conservation Service (SCS), Design Section. Mr. Richard Peace, State Conservation Engineer, SCS office, Jackson, MS, was instrumental in defining the scope and direction of this study.

COL Larry Fulton, EN, was Commander and Director of WES during preparation of this report. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| cubic feet | 0.02831685 | cubic metres |
| feet | 0.3048 | metres |
| inches | 2.54 | centimetres |
| pounds | 0.4535924 | kilograms |
| pounds (mass) per cubic foot | 16.01846 | kilograms per cubic metre |

SOIL CONSERVATION SERVICE LOW DROP STRUCTURE MODEL STUDY

Hydraulic Model Investigation

## PART I: INTRODUCTION

1. The US Department of Agriculture Soil Conservation Service (SCS) has been using a loose riprap grade control structure design based on an equal energy concept for several years. Construction of several of these structures on the Muddy Creek system resulted in severe scour problems immediately downstream from the grade control or drop structures. Flow separation in the exit flare was identified as the source of the problem and research was conducted to determine methods to reduce the scour (TR HL-88-11).* The Muddy Creek structures have 1:4- or 1:8-exit flares, and model tests indicated that a series of H-pile baffles placed in the exit transitions would prevent flow separation and reduce scour. Additional tests during the Muddy Creek study indicated that a 1:16-exit flare would be required to prevent flow separation without the H-pile baffles. This flare ratio, in addition to the long prismatic drop section needed with the equal energy design, would result in an extremely long structure and significantly increase the costs of constructing drop structures. This research was subsequently undertaken to develop a different design which would decrease the costs of loose riprap drop structures. A second objective was to develop a design methodology for the new design that would be applicable.

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* Charles H. Tate, Jr. 1988 (May). "Muddy Creek Grade Control Structures, Muddy Creek, Mississippi and Tennessee," Technical Report HL-88-11, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

## PART II: PHYSICAL MODEL

### Description

2. A 1:20-scale model was used to test several designs that incorporated a single riprap gradation. These designs were based on the maximum requirements for a structure of this type, as determined by the SCS, to include a maximum flow of 5,000 cfs in a trapezoidal channel with a base width of 120 ft, a flow depth of 10 ft, 1V:2H-side slopes, a Manning's $n$ value of 0.030, and a 0.0003 slope. The drop structure was to be placed in the channel, include up to 4 ft of drop, and be constructed of loose riprap. Implied in grade control design is the requirement to maintain the channel flow depth at the upstream end of the drop structure. The model was constructed in a tilting flume with plastic coated plywood entrance and exit channels. The drop structure was constructed with graded crushed limestone overlying a sand base.

3. Flow to this model was supplied through a circulating system. Discharges were measured with differential pressure manometers and controlled with a gate valve. Point gages were used to measure water-surface elevations throughout the model. Velocities were measured in the model with propeller meters. Flow conditions were observed for the different designs tested with flow conditions being recorded photographically.

### Scale Relations

4. The accepted equations of hydraulic similitude, based on the Froudian criteria, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for the transference of model data to prototype equivalents are in the following tabulation. Model measurements of discharge, water-surface elevations, and velocities can be transferred quantitatively to prototype equivalents by means of the scale relations. Previous experimental data also indicate that the model-to-prototype scale ratio is valid for scaling stone in the sizes used in this investigation.

| Characteristic | Dimension* | Scale Relations Model:Prototype |
|---|---|---|
| Length | $L_r$ | 1:20 |
| Area | $A_r = L_r^2$ | 1:400 |
| Velocity | $V_r = L_r^{1/2}$ | 1:4.472 |
| Discharge | $Q_r = L_r^{5/2}$ | 1:1,788 |
| Volume | $V_r = L_r^3$ | 1:8,000 |
| Weight | $W_r = L_r^3$ | 1:8,000 |
| Time | $T_r = L_r^{1/2}$ | 1:4.472 |

* Dimensions are in terms of length.

## PART III: TESTS AND RESULTS

5. Tests were conducted to determine the flow characteristics through the various drop structure designs used in this study. The major areas of concern included the depth of the flow entering the structure, flow conditions and riprap stability through and downstream of the throat section, flow uniformity in the exit transition, and balanced flow velocities exiting the structure.

6. The initial structure tested incorporated the drop section with the exit flare so that the 4-ft drop occurred within the exit flare. Based on recent riprap research at the US Army Engineer Waterways Experiment Station (WES),* assumed flow parameters and the prototype riprap gradation shown in the following tabulation and Plate 1, an initial slope of 0.009 was used for the drop section.

| Stone Weight lb | Cumulative Percent Lighter by Weight |
|---|---|
| 1,500 | 100 |
| 650 | 50-100 |
| 330 | 15-50 |
| 100 | 0-15 |

The model riprap gradation as shown in Plate 1 is generally on the lightweight side of the prototype gradation to ensure conservative results from the model study. The slope in the approach and throat section was arbitrarily set at one-half the drop slope (0.0045). Using these slopes and uniform flow equations for a discharge of 5,000 cfs, the required throat width to maintain the upstream flow depth was determined to be 35 ft. The exit flare was extended to the end of the drop section resulting in a 1:10.6-exit flare. The approach converged at 1:2 from a 120-ft-wide base width to a 35-ft-wide throat section that was set at 10 ft long. The 10-ft length was based on a minimum reasonable dimension that can be constructed with heavy equipment. At the downstream end of the throat section, the drop slope started as well as the exit flare. This design (Design 1) is shown in Photo 1 and Plate 2. Unsatisfactory flow conditions were observed in this structure with flow following

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* Headquarters, US Army Corps of Engineers. "Hydraulic Design of Flood Control Channels" (revision in preparation), EM 1110-2-1601, US Government Printing Office, Washington, DC.

along one side of the exit flare, resulting in a strong eddy on the opposite side of the flare. The rating curve determined from the model indicated the structure passed 5,009 cfs at the 10-ft flow depth in the approach channel. This was obviously an unsatisfactory design with flow separation in the exit flare. Consequently, no additional data were collected.

7. The drop structure was modified with a 1:12-exit flare. The additional invert length required due to the longer exit flare was placed on the channel slope (Design 2). Flow still concentrated causing eddies to form in the exit flare (Photo 2). Based on flow conditions in the throat section, the throat section was lengthened from 10 to 50 ft to form Design 3. However, with this modification, flow conditions did not improve.

8. The flume was then tilted to determine the maximum slope for the drop section on which the loose riprap would remain stable. These tests indicated deformation of the invert occurred at slopes above 0.020. The initial design was based on recent riprap research that had a blanket thickness equal to the maximum rock size. The model design used a blanket thickness equal to 1.5 times the maximum rock size and was significantly more stable compared to the research.

9. Numerical analysis was also conducted at WES to assist in maximizing the throat width which would minimize the length of the exit flare. Two numerical codes, HEC-2 and WASP2, were compared to the physical model results. Both codes calculate flow parameters for steady and gradually varied flow. HEC-2 was developed at the Hydrologic Engineering Center in Davis, CA, by Mr. Bill S. Eichert* and is a complex code which handles highly variable cross sections and contains many options. WASP2 was developed in the California SCS Design Section by Messrs. Donald E. Twiss and David J. Sarvary** and is designed for trapezoidal channels. Based on these comparisons and the simplicity of using WASP2, WASP2 was used for the remaining analysis. Existing documentation for this code is in Appendix A. By setting the approach and throat section slopes at the channel slope, the maximum throat width that would maintain the channel flow depth at the upstream end of the

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* Hydraulic Engineering Center. 1990 (Sep). "HEC-2, Water-Surface Profiles, User's Manual, CPD-2A, Hydraulic Engineering Center, Davis, CA.

** Twiss, Donald E., and Sarvary, David J. 1985 (Mar). "Water-Surface Profiles, Rectangular and Trapezoidal Channels," USDA Soil Conservation Service, Davis, CA.

drop structure could be determined. For the riprap shown in the previous tabulation and no form losses in the numerical analysis, this resulted in a throat width of 37.5 ft.

10. The model was rebuilt (Design 4) with the approach and throat slope at the channel slope and the 1:2 convergence to a 37.5-ft-wide by 10-ft-long throat. The exit flare was set to 1:14 and the 0.020-drop slope started at the downstream end of the throat and dropped 4 ft. For the downstream 377.5 ft, the invert followed the channel slope to the end of the exit flare (Plate 3). This structure appeared to be stable, and the downstream flow extended all the way across the channel at the downstream end of the structure (Photo 3). However, at the downstream end of the structure a significant velocity gradient existed near the banks, and velocities near the center of the channel were greater than 6 fps (channel design is for an average velocity of 3.6 fps based on the channel dimensions, 5,000 cfs flow, and a 10-ft-flow depth), as shown in Plate 4. Additionally, this structure passed only 4,350 cfs at the 10-ft-design approach depth compared to the design flow of 5,000 cfs.

11. Standard convergence and expansion form loss coefficients of 0.2 and 0.3, respectively, were included in the WASP2 calculations resulting in a 42-ft throat width. Design 5 included the 42-ft throat width with a 1:14-exit flare. This design passed 5,140 cfs at the 10-ft-design approach depth without eddies at the downstream end of the structure. However, exit velocities were much higher in the center of the exit channel than toward the sides and skewed toward the right bank as shown in Plate 5. This indicates that flow still has a tendency to separate from the exit flare. The maximum velocity was 6.0 fps.

12. The model was modified to a 1:16-exit flare (Design 6, Plate 6), which passed 5,078 cfs at the 10-ft-design approach depth. Exit velocities were centered in the channel and varied much more gradually from the center toward the edge of the exit channel, as shown in Photo 4 and Plate 7. Plate 8 compares the observed water surface to the water surface computed using WASP2 with standard form loss coefficients.

13. The design parameters developed during this study were combined with a riprap stability equation to develop a method for designing loose riprap grade-control structures. Knowing the basic hydraulic information and the geometry of the drop structure developed from this study, backwater

calculation is made through the entire structure to determine the water-surface profile, flow depth, and average velocity. Adjustments are made to the throat width of the structure until the water surface at the upstream end of the structure matches the design flow depth. The riprap stability equation is then used to determine the required size and thickness of riprap. Details of the design methodology are shown in Appendix B.

## PART IV: CONCLUSIONS AND RECOMMENDATIONS

14. The primary requirement for this study was to develop a drop structure design which cost less to install than the current design. The Design 6 drop structure satisfies the purpose and requirements of this investigation. Although the new design still requires a 1:16-exit flare to produce an acceptable velocity distribution at the downstream end of the structure, the overall length of the structure is reduced considerably. When the physical arrangement of the Design 6 drop structure is coupled with numerical codes and riprap stability criteria, an overall design methodology is available. The design methodology is detailed in Appendix B of this report and is included as a separate document so that it may be readily transferred to other documents dealing with designing this type of grade control structure.

15. By using the design methodology in Appendix B, the overall length of the resulting drop structure will be approximately 60 to 70 percent of the required length of the current design. A major cost saving may come from the ability, with the new design, to reduce the riprap layer thickness and to replace some of the exit riprap with smaller riprap with a reduced blanket thickness. These changes will significantly reduce the volume of riprap required to construct drop structures.

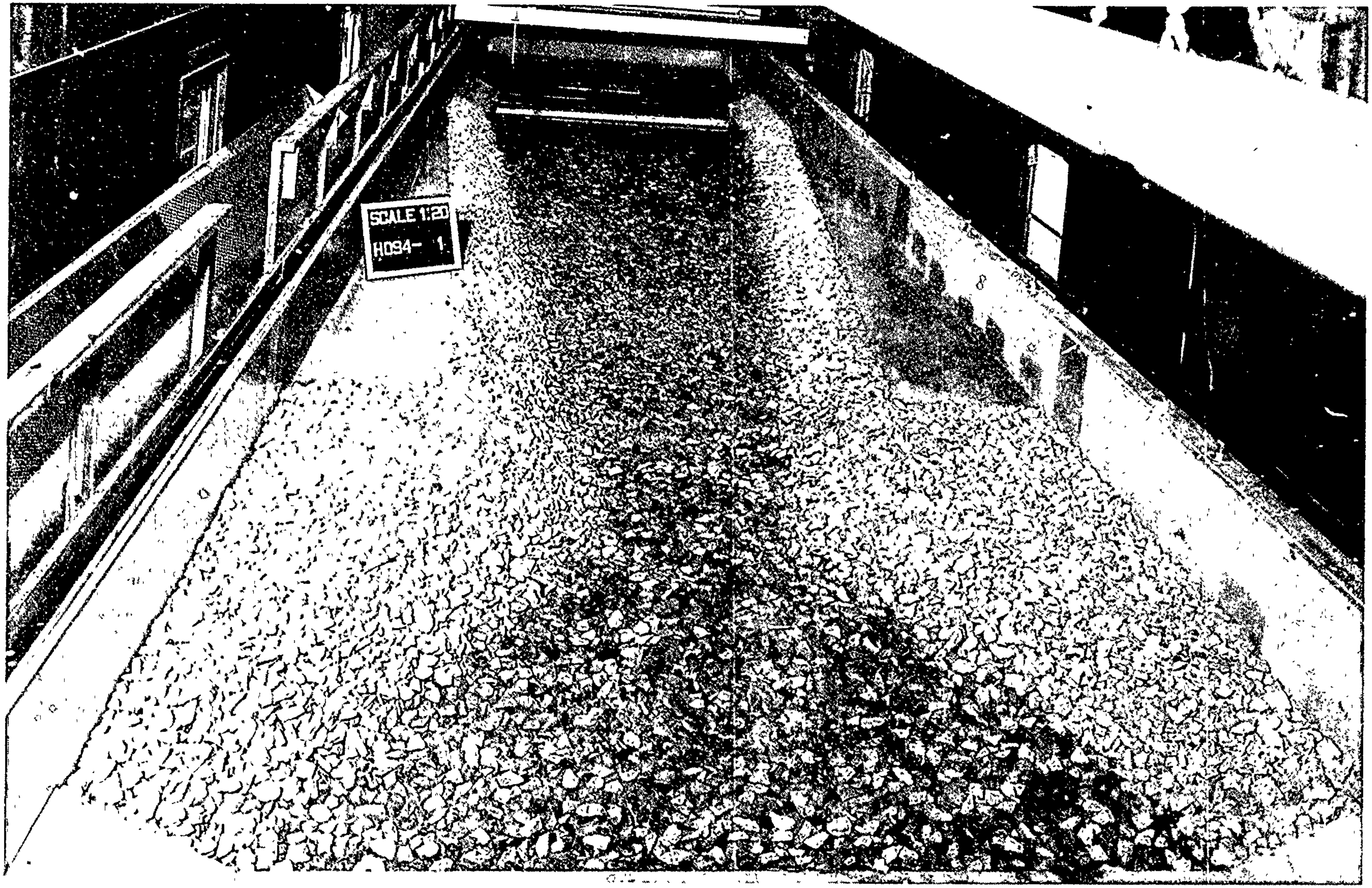



Photo 1. Design 1 dry bed, downstream view

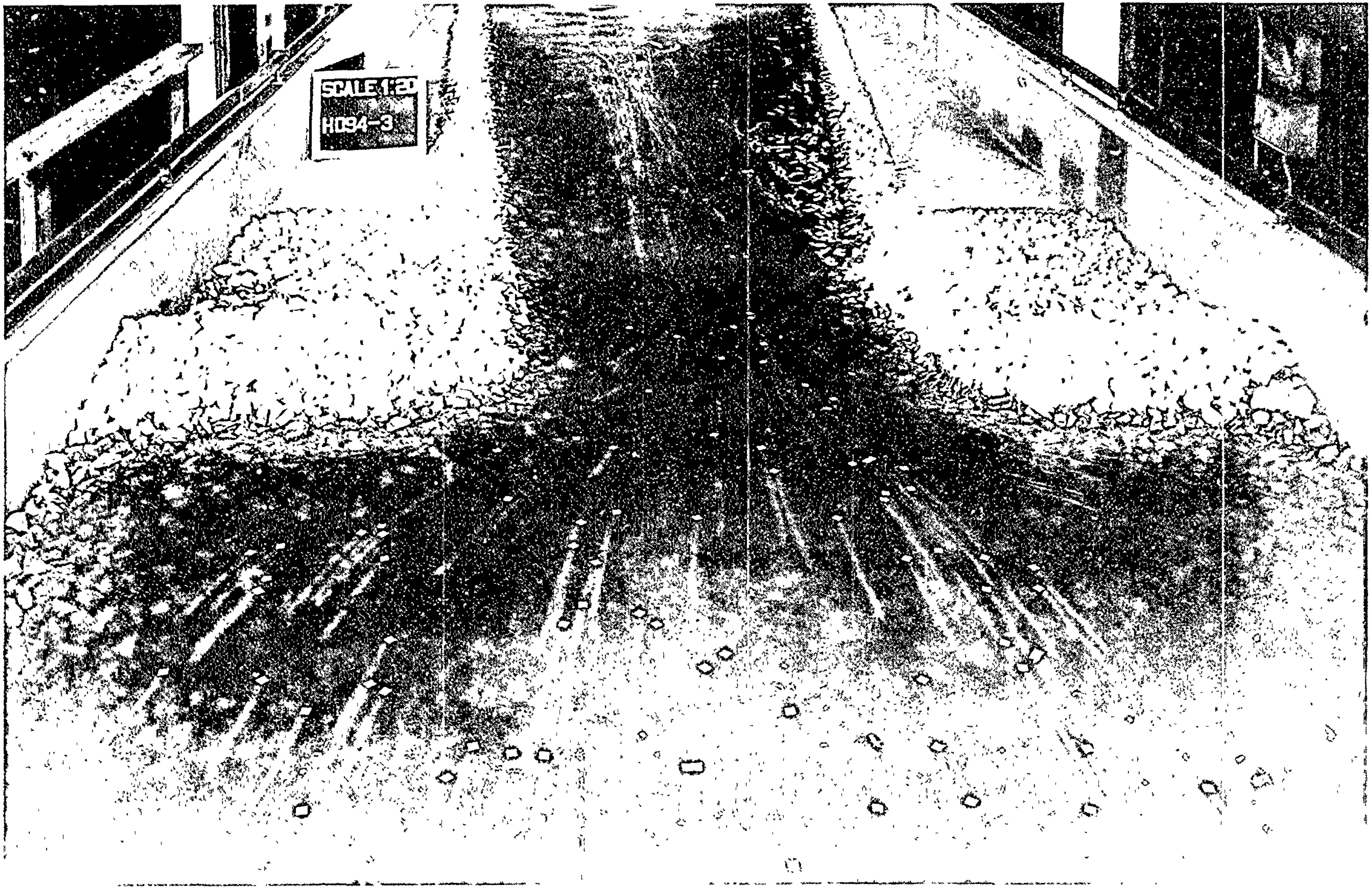



Photo 2. Design 2 with exit flow concentration to the left and an eddy to the right

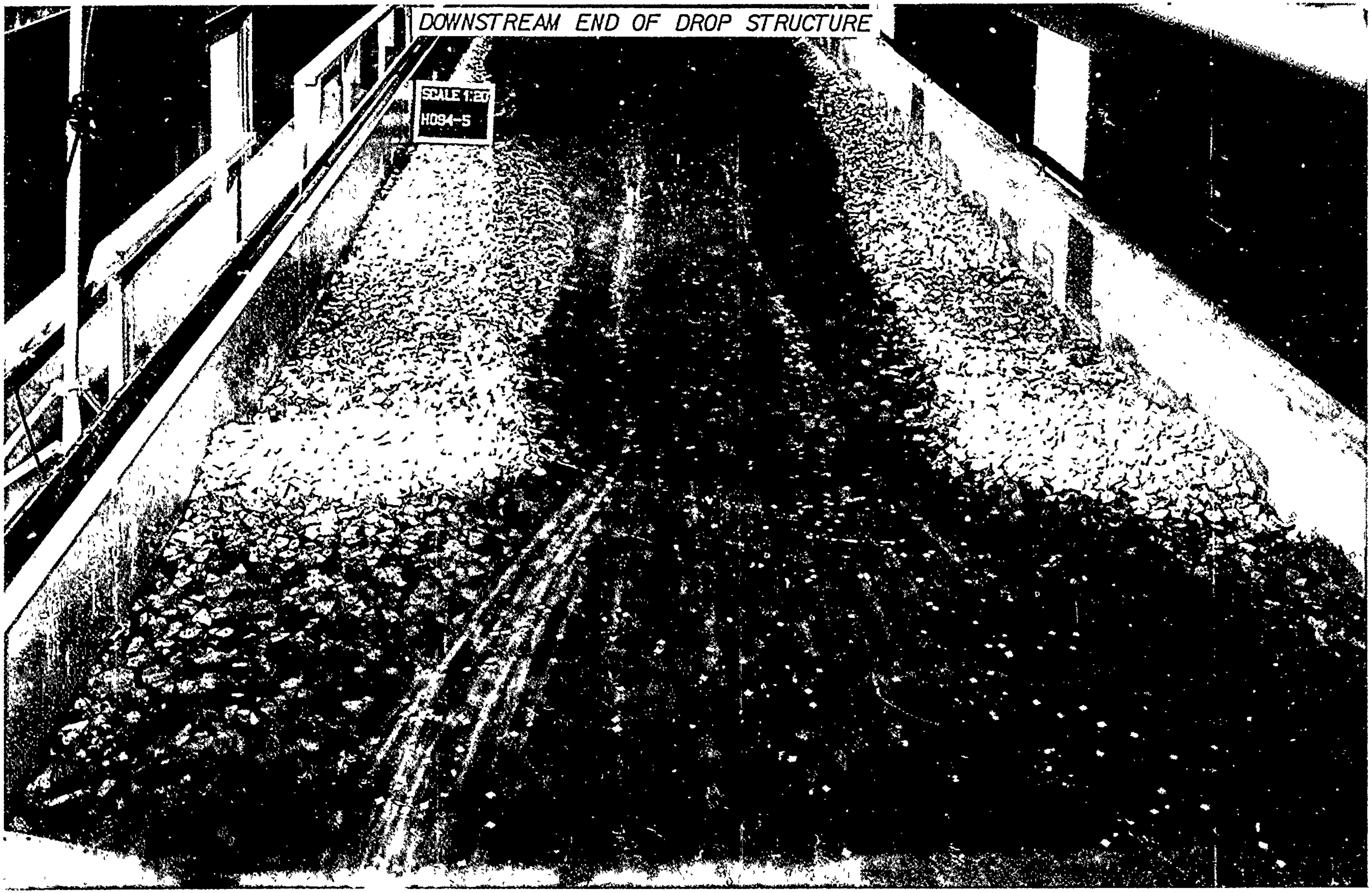
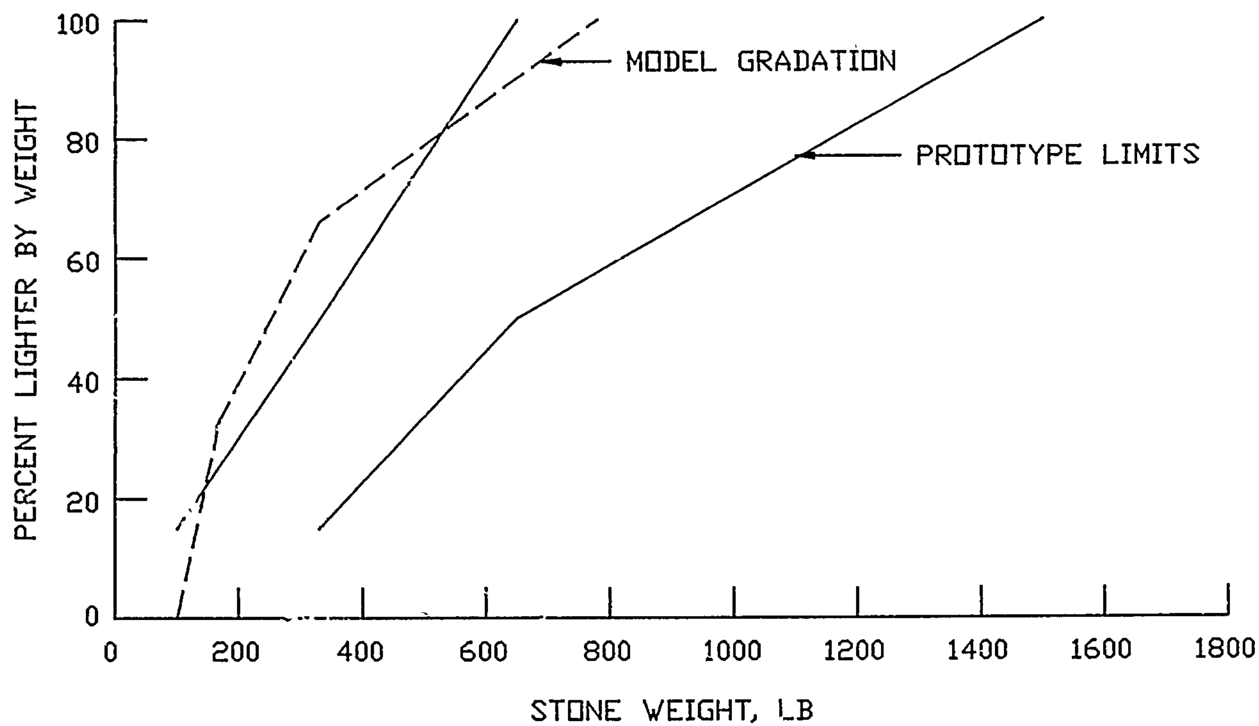


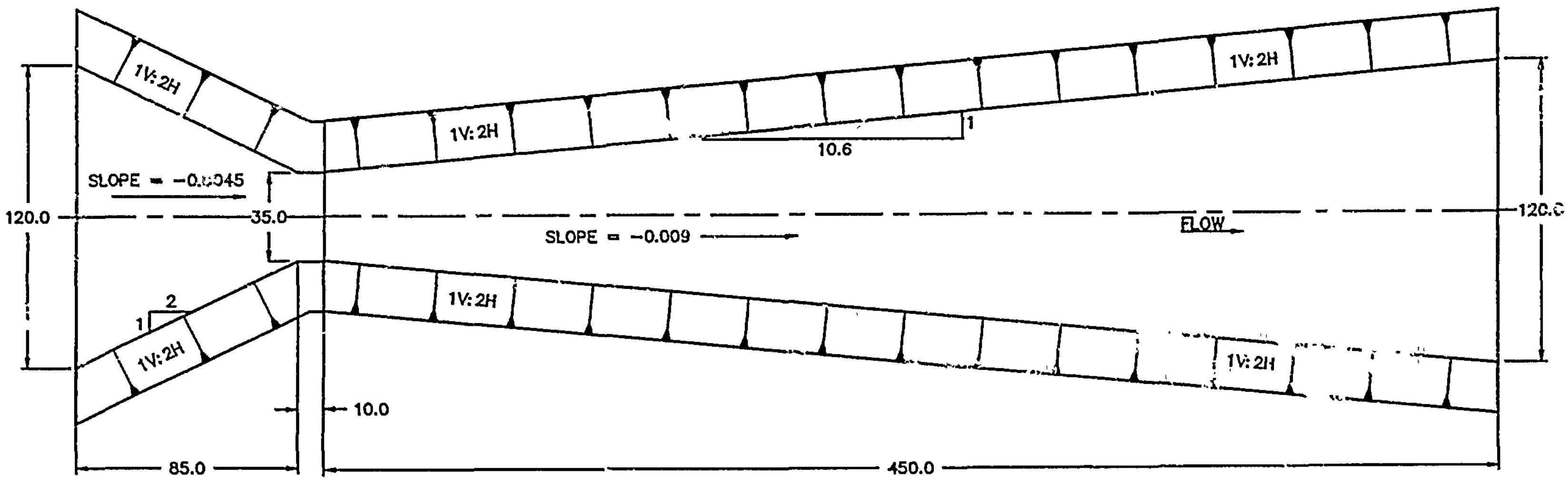

Photo 3. Design 4 surface flow patterns


Photo 4. Design 6 surface flow patterns




RIPRAP GRADATION

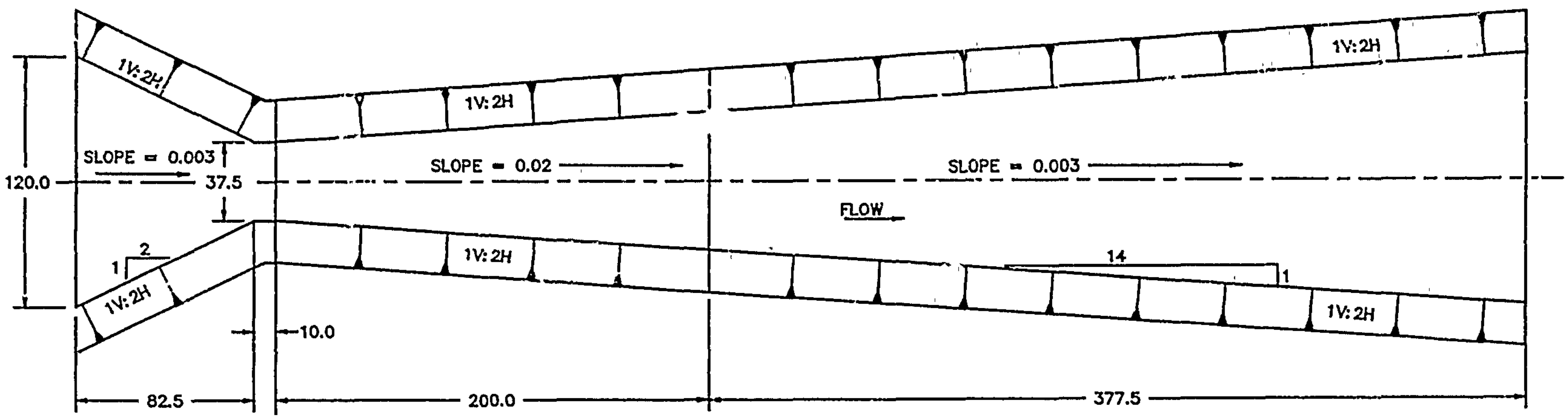
BLANKET THICKNESS = 48 IN.
SPECIAL WEIGHT OF STONE:
160 POUNDS / CUBIC FT.
$D_{50}$ = 17.5 IN.




SCS LOW DROP STRUCTURE
DESIGN 1

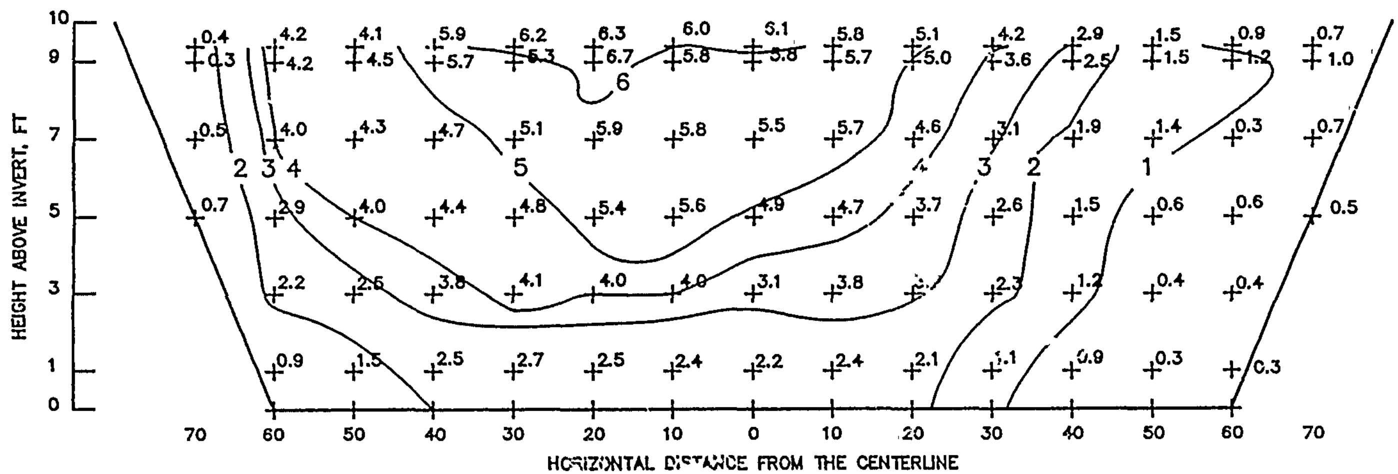
NOTE: DIMENSIONS ARE IN PROTOTYPE FEET

PLATE 2



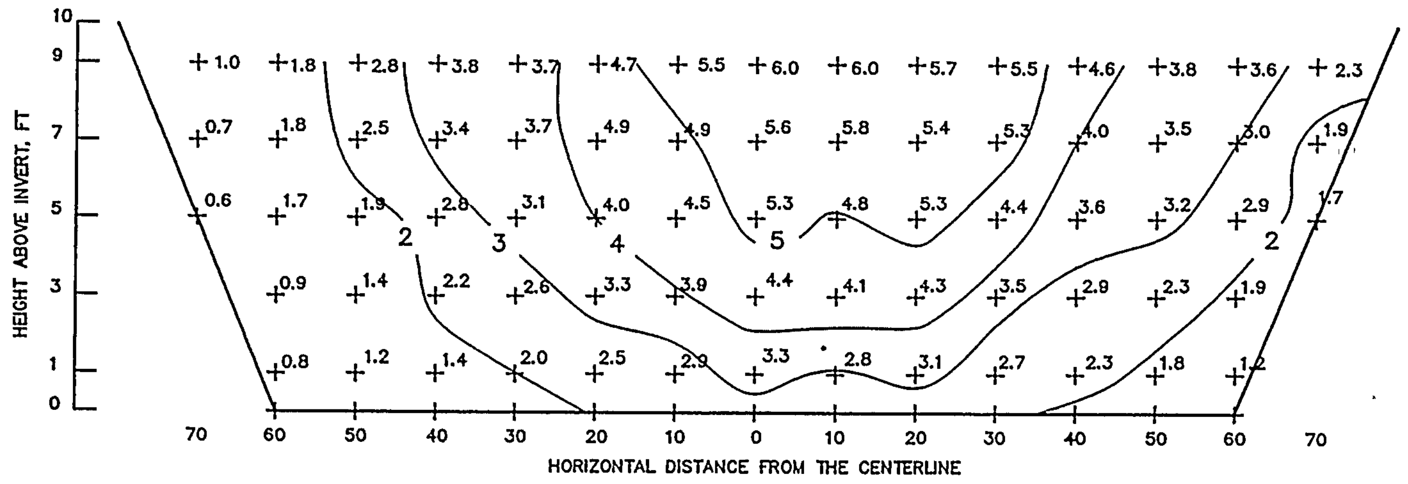

NOTE: DIMENSIONS ARE IN PROTOTYPE FEET

**SCS LOW DROP STRUCTURE**
**DESIGN 4**



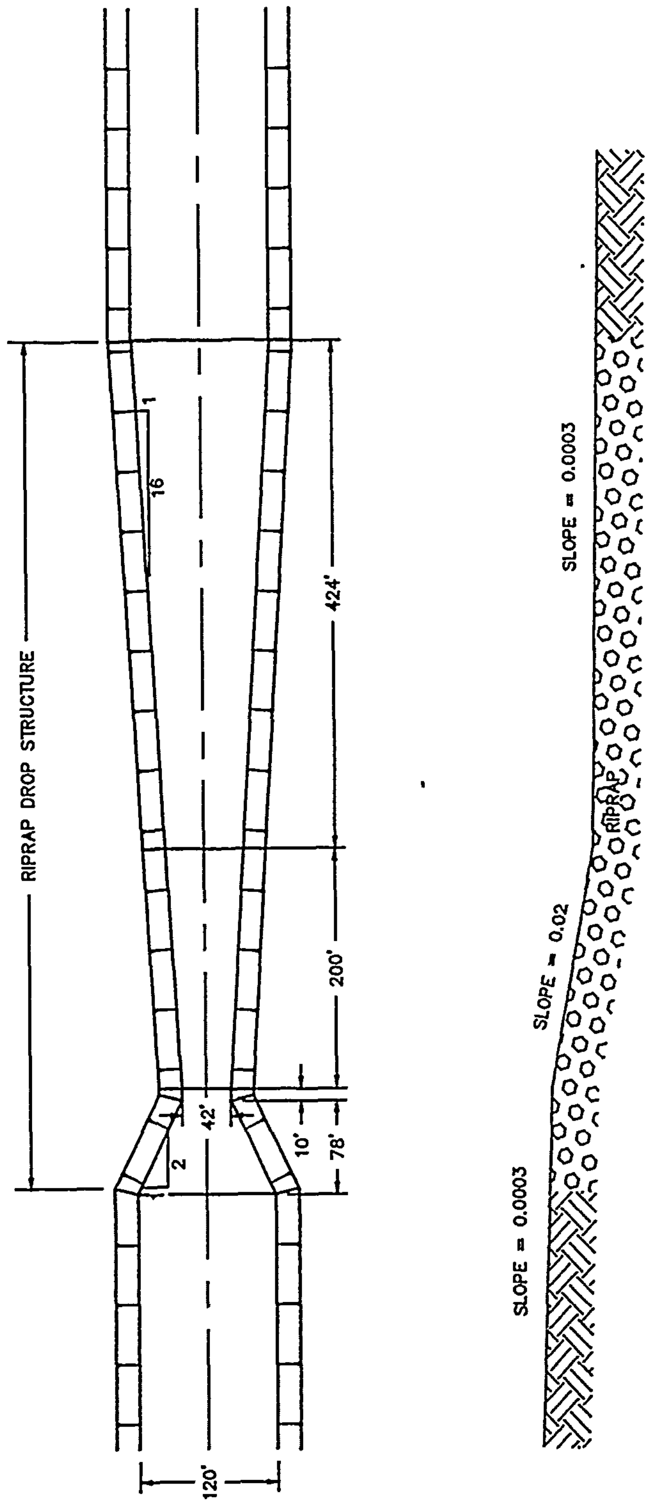

NOTE: VELOCITIES ARE REFERENCED TO LOOKING IN THE DOWNSTREAM DIRECTION

**VELOCITY CROSS SECTION**
DOWNSTREAM END OF DROP STRUCTURE
DESIGN 4
FLOW = 4,500 CFS
FLOW DEPTH = 10 FT

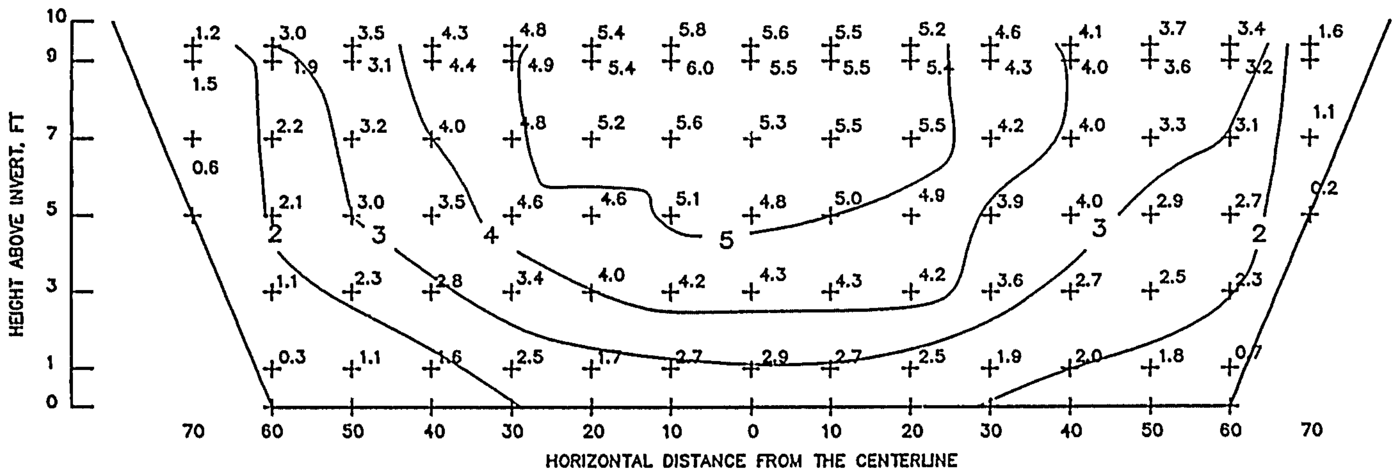



NOTE: VELOCITIES ARE REFERENCED TO LOOKING IN THE DOWNSTREAM DIRECTION

**VELOCITY CROSS SECTION**
DOWNSTREAM END OF DROP STRUCTURE
DESIGN 5
FLOW = 5,140 CFS
FLOW DEPTH = 10 FT




SCS LOW DROP STRUCTURE
DESIGN 6




NOTE: VELOCITIES ARE REFERENCED TO LOOKING IN THE DOWNSTREAM DIRECTION

**VELOCITY CROSS SECTION**
DOWNSTREAM END OF DROP STRUCTURE
DESIGN 6
FLOW = 5,078 CFS
FLOW DEPTH = 10 FT

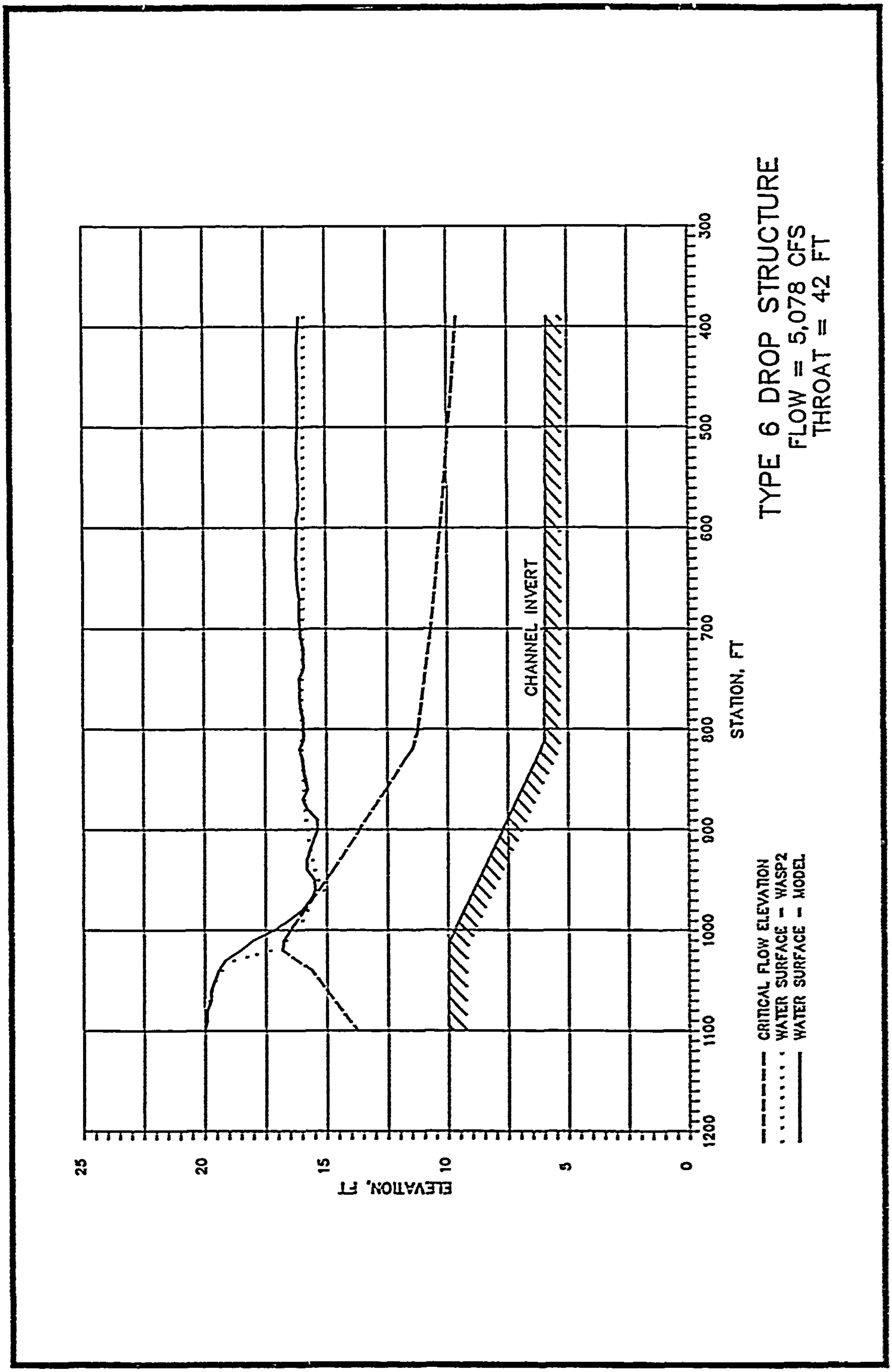

TYPE 6 DROP STRUCTURE
FLOW = 5,078 CFS
THROAT = 42 FT
ELEVATION, FT
STATION, FT
CHANNEL INVERT
CRITICAL FLOW ELEVATION
WATER SURFACE – WASP2
WATER SURFACE – MODEL
25
20
15
10
5
0
1200
1100
1000
900
800
700
600
500
400
300

PLATE 8

# APPENDIX A: WATER-SURFACE PROFILES RECTANGULAR AND TRAPEZOIDAL CHANNELS

COMPUTER PROGRAM WASP2.BAS

# WATER SURFACE PROFILES
# RECTANGULAR AND TRAPEZOIDAL
# CHANNELS

MARCH 1985

REVISED AUGUST 1985

USDA SOIL CONSERVATION SERVICE
2828 CHILES ROAD
DAVIS, CALIFORNIA 95616

## SUMMARY

This program is intended for calculating water-surface profiles for steady, gradually varied flow in man-made channels. Both subcritical and supercritical flow profiles can be calculated. The computational procedure is based on the solution of the one-dimensional energy equation with energy loss due to friction evaluated with the Manning's equation. The Standard Step Method is used to compute the water-surface profile.


## COMPUTER EQUIPMENT REQUIREMENTS

The WASP2 computer program was written for use on the Seattle Gazelle computer but may be used with little or no change on most microcomputers with the Basic language.

## PROGRAM DEVELOPMENT

The WASP2 computer program was developed in the California SCS Design Section by Donald E. Twiss and David J. Sarvary. The program is derived from the general-purpose trapezoidal channel hydraulics program HYDRA developed by John Hanes. The water-surface profile portion of HYDRA was enhanced with data file and preprocessor features for creating and storing input values.

## THEORETICAL BASIS FOR CALCULATIONS

1. EQUATIONS FOR BASIC PROFILE CALCULATION

The following equations are solved by an iterative procedure to calculate an unknown water-surface elevation at a cross section (Figure A1).

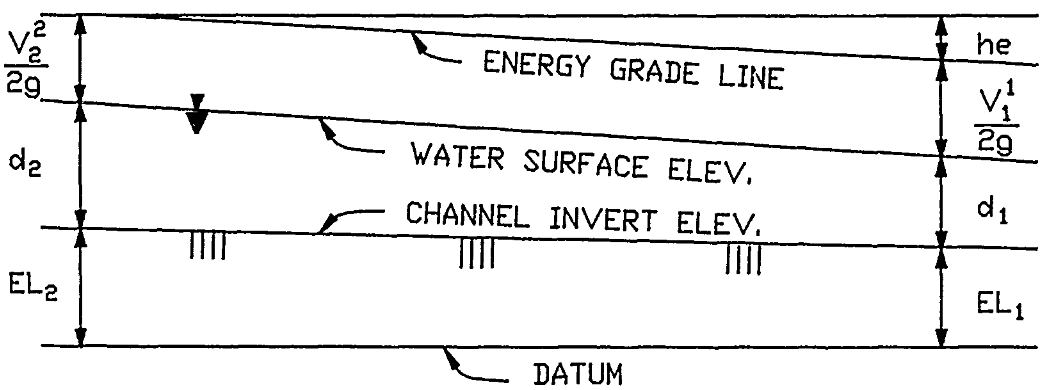



Figure A1. Channel profile

$$WS_2 + \frac{V_2^2}{2g} = WS_1 + \frac{V_1^2}{2g} + h_e \quad \text{(A1)}$$

$$h_e = LS_f + C\left[\frac{V_2^2}{2g} - \frac{V_1^2}{2g}\right] \quad \text{(A2)}$$

where

$WS_1$, $WS_2$ = water-surface elevations (feet)
= depth + invert elevation

$V_1$, $V_2$ = mean velocities (feet per second)
= discharge/area

g = acceleration of gravity (feet squared per second)

El = invert elevation (feet)

$h_e$ = energy head loss (feet)

$S_f$ = representative friction slope between cross sections

C = expansion or contraction loss coefficient

L = distance between cross sections (feet)

The conveyance K is from the Manning's equation.

$$K = 1.486\ ar^{2/3} \tag{A3}$$

where

K = conveyance

a = flow area (feet squared)

r = hydraulic radius (feet)

The friction loss is evaluated as the produce of $S_f$ and L .

$$S_1 = \left[\frac{(Q_1 + Q_2) \times n}{K_1 + K_2}\right]^2 \tag{A4}$$

where

$Q_1$, $Q_2$ = discharge or flow at each cross section (cubic feet per second)

$K_1$, $K_2$ = conveyance at each cross section

n = Manning's n

The other equations used in this program are particular to rectangular and trapezoidal prismoidal channels (Figure A2).

$$a = bd + Zd^2 \tag{A5}$$

$$p = b + 2d(Z^2+1)^{1/2} \tag{A6}$$

$$r = a/p \tag{A7}$$

$$T = b + 2Zd \tag{A8}$$

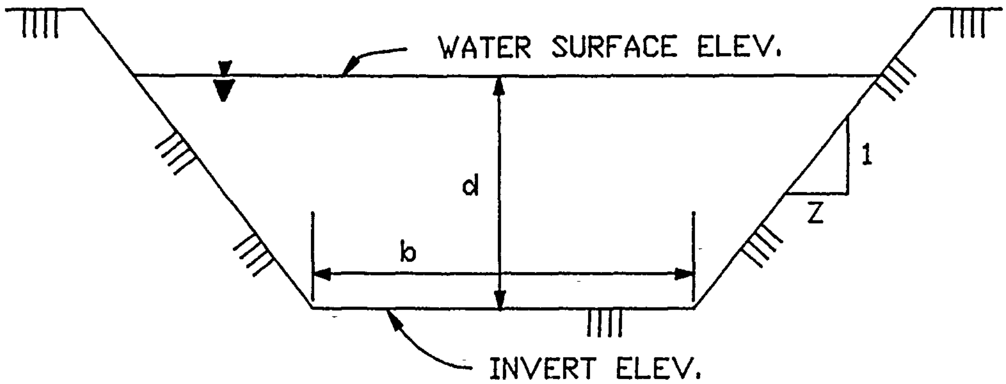



Figure A2. Channel cross section

$$Fr = \frac{V}{(ga/T)^{1/2}} \tag{A9}$$

where

$a$ = area (feet squared)

$d$ = depth (feet)

$p$ = wetted perimeter (feet)

$r$ = hydraulic radius (feet)

$T$ = top width (feet)

$Fr$ = Froude Number

$b$ = bottom width (feet)

$Z$ = side slope (Z:1)

2. EQUATIONS FOR PRESSURE AND MOMENTUM

Sequent depth is calculated by the pressure and momentum equations for use in determining hydraulic jump characteristics.

$$P_1 + M_1 = P_2 + M_2 \tag{A10}$$

$$P = \frac{d^2}{6}(3b + 2Zd) \tag{A11}$$

$$M = \frac{Q^2}{(b + Zd)gd} \tag{A12}$$

where

$P_1$, $P_2$ = hydrostatic pressures (feet cubed)

$M_1$, $M_2$ = momentum (feet cubed)

3. EQUATIONS FOR FREEBOARD

Freeboard is calculated from the following equations:

| | Subcritical | Supercritical |
|---|---|---|
| Rectangular section | 0.1He | 0.2d |
| Trapezoidal section | 0.2He | 0.25d |

where

He = specific energy head (feet)

d = depth (feet)

## BASIC DATA REQUIREMENTS

A major portion of the programming in WASP2 is devoted to providing a simple and quick method for computing water-surface profiles in man-made rectangular or trapezoidal channels. The data needed to perform these computations are:

1. Flow regime (subcritical/supercritical)
2. Beginning depth - d - (feet)
3. Station - sta - (feet)
4. Flow - Q - (c.f.s.)
5. Bottom width - B - (feet)
6. Side slope - Z - (feet/feet)
7. Invert elevation - EL - (feet)
8. Manning's n - n -
9. Transition loss coefficient - C -

## DATA FILE PROCESSING

The WASP2 program has an extensive data base management system built in. The program is menu driven to reduce the effort in learning to use the program. The following options are available from the main menu:

1. View
2. Search (by Station)
3. Add to or create a file
4. Change (by Station)
5. Data file processor
6. Delete (by Station)
7. Delete (Station to Station)
8. Save
9. Load
10. Print
11. Sort list (by Station)

12. Compute water-surface profile

13. Finish session

DESCRIPTIONS OF OPTIONS

1. VIEW

   The view option allows the array in memory to be shown on the monitor.

2. SEARCH

   The Search by Station option can be used to check the other variables at a station of interest.

3. ADD TO OR CREATE A FILE

   The Add or Create option allows data to be input to memory for one station at a time. This is particularly useful to add stations between those at an even increment prior to using the Data File Processor option. The other variables such as flow, bottom width, etc., can be added later with the Data File Processor option.

4. CHANGE (BY STATION)

   The Change by Station option is similar to the Search by Station option but allows editing of the variables at the station of interest.

5. DATA FILE PROCESSOR

   The Data File Processor option allows rapid data file construction by automatically adding repetitious values to the array in memory. The beginning and ending station is entered for all variables that are constant or vary linearly. The program adds the value of the variable entered to all stations found in the array between and including the stations entered. The following variables may change linearly from the beginning station to the ending station:

   a. Bottom width

   b. Side slope

   c. Invert elevation

   The beginning station must always be smaller than the ending station when using the Data File Processor option. This makes it preferable to build the data file from the smallest station to the largest station. The file can then be sorted using the Sort option to go upstream or downstream for subcritical or supercritical flow, respectively.

6. DELETE (BY STATION)

   The Delete by Station option allows single stations along with the other variables at that station to be deleted. This is particularly useful when two stations with the same value have been entered. The program will not run with two stations of the same value.

7. DELETE (STATION TO STATION)

   This option will delete all stations and their associated variables from and including the beginning to the ending station entered.

8. <u>SAVE</u>

This option writes the array in memory to a permanent disk file with the file name specified by the user.

9. <u>LOAD</u>

This option reads the data file specified by the user to an array in memory for editing or viewing.

10. <u>PRINT</u>

This option allows a "Saved" data file to be sent to the printer for a hard copy.

11. <u>SORT LIST (BY STATION)</u>

This option is used to arrange in order the stations with their associated variables in memory. This should be done before saving all data sets. For subcritical flow the order is from downstream to upstream. For supercritical flow the order is from upstream to downstream.

12. <u>COMPUTE WATER-SURFACE PROFILE</u>

This option reads a "Saved" data file from disk, calculates the water-surface profile, and prints the output on the printer.

13. <u>FINISH SESSION</u>

This option returns the computer to basic.

# APPENDIX B: TYPE 6 DROP STRUCTURE DESIGN METHOD

1. The following is the method used to design the type 6 drop structure that was developed for the Soil Conservation Service (SCS). This design was requested to provide an alternative to the SCS prismatic channel drop structure which is based on the equal energy concept and described by the SCS* where current guidance calls for a 1:16-exit flare.

2. The type 6 drop structure has a 1:2-converging entrance on the channel slope to a 10-ft-long throat section also on the channel slope (Figure B1). At the downstream end of the throat section, the drop slope

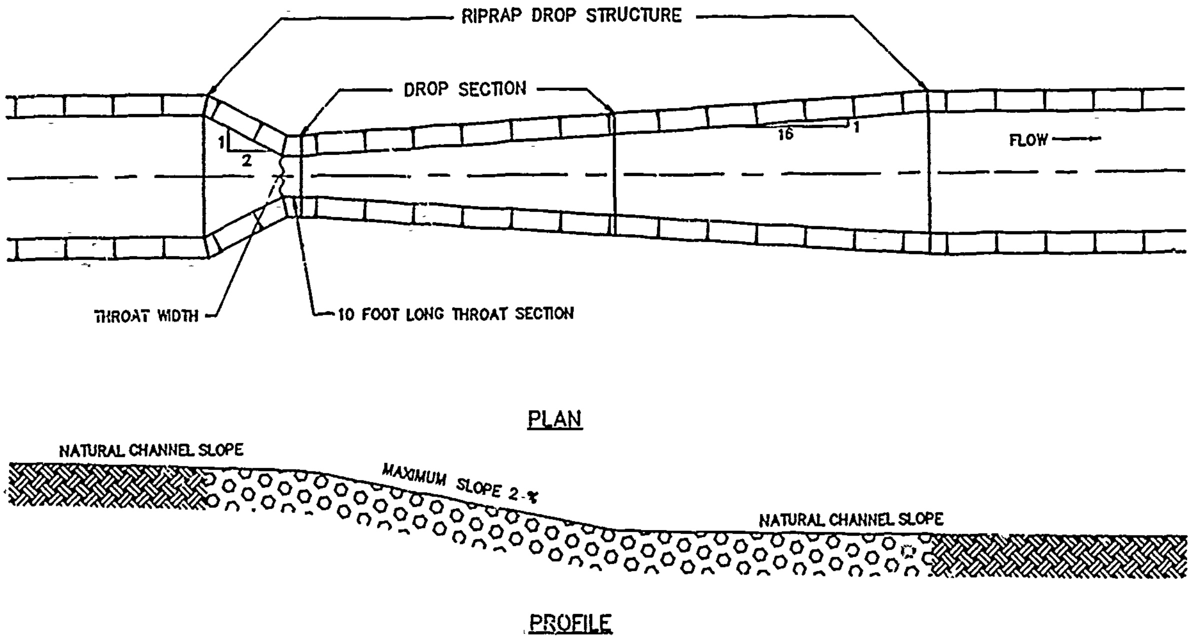



Figure B1: Schematic of type 6 drop structure

starts as well as the 1:16 exit flare. The drop slope is limited to a maximum of 2 percent and a Froude Number ($F_n$) of 1.3. Downstream of the drop slope the invert is again on the channel slope. The entire drop structure is designed to be built from loose riprap with 1V:2H-side slopes. Results of other model studies indicate that the entering and exiting side slopes may be flatter (1V:3H) with the side slopes in the entrance and exit transitioning to 1V:2H in the throat section. The design method describes how to size the throat width and determine riprap stability.

3. Prior to designing the drop structure, the channel geometry and

* Soil Conservation Service. 1976 (23 Jan). "Hydraulic Design of Riprap Gradient Control Structure," Technical Release No. 59 and Amendment 1 dated 10 April 1986, US Department of Agriculture, Washington, DC.

design flow must be known. The channel slope will be used in the drop structure as the entrance and exit slope. The base width and flow depth based on 1V:2H-side slopes are used as the upstream and downstream geometry of the drop structure.

4. Typically, several riprap gradations are available. It is possible to calculate the riprap size that is needed for a drop structure or to determine if a given riprap size is stable for the flow conditions to which it is subjected.* Assuming a given riprap gradation, both the $d_{90}$ and the $d_{30}$ sizes are needed. The $d_{90}$ size is the nominal diameter in feet of which 90 percent of the riprap is smaller. The $d_{30}$ size is the nominal diameter in feet of which 30 percent of the riprap is smaller. The Manning's $n$ value for the riprap can be estimated using Strickler's equation

$$n = 0.035\ d_{90}^{1/6} \tag{B1}$$

where $d_{90}$ is used instead of the traditional $d_{50}$ due to data fitting results by Maynord.**

5. A backwater calculation is used to determine the required throat width to pass the design flow at the upstream natural channel design flow depth. WASP2 is a numerical code that performs well in comparison to physical model results and is designed for trapezoidal channels. This is the code that will be mentioned in this design method although any good backwater code that can calculate both supercritical and subcritical flow parameters can be used. The calculations require an initial geometry for the drop structure. An initial throat width of one-third the channel width is a reasonable first approximation. The drop structure converges from the channel width to the throat section at a 1:2 rate with the convergence at the channel slope. The throat section is 10 ft long at the channel slope. Both the drop slope and the 1:16-exit flare start at the downstream end of the throat section. The drop slope should be limited to 2 percent based on the limits of the data used to determine the riprap stability criteria and can drop any vertical distance

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* Headquarters, US Army Corps of Engineers. "Hydraulic Design of Flood Control Channels" (in preparation), EM 1110-2-1601, US Government Printing Office, Washington, DC.

** S. T. Maynord. 1987. "Stable Riprap Size for Open Channel Flows," Ph.D. dissertation, Colorado State University, Fort Collins, CO.

(the model study was limited to 4 ft) as long as the $F_n$ entering the tailwater is less than 1.3. A higher $F_n$ entering the tailwater creates turbulence that may cause the riprap to fail. Any remaining exit flare is at the channel slope. If the structure has a large drop and the drop slope extends beyond the exit flare, then the remaining drop slope should extend downstream at the channel width, and a short reach of the channel slope invert should be protected with riprap immediately downstream of the drop slope. Form loss coefficients for the converging and flaring sections are 0.2 and 0.3, respectively, which are the values usually found in the literature. A subcritical flow analysis usually identifies an area downstream of the throat section that may be supercritical. During the subcritical calculations, critical depth should be assumed for these locations. The throat width can be varied until the upstream channel design flow depth exists at the upstream end of the drop structure. Once the throat width is determined, a supercritical flow analysis of the portion of the structure where critical flow was assumed can be superimposed on the subcritical analysis to approximate the water surface in the entire structure. Again, the $F_n$ entering the tailwater should not exceed 1.3.

6. From the velocities and flow depths computed by WASP2, the $d_{30}$ can be determined and compared to the chosen riprap gradation. These factors are combined in the equation

$$d_{30} = F_s c C_3 D \left[ \left( \frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{gD}} \right]^{2.5} \qquad \text{(B2)}$$

where

$d_{30}$ = the nominal diameter of which 30 percent of the riprap is smaller, feet

$F_s$ = factor of safety

$c$ = stability coefficient, 0.30 for incipient failure, thickness = $1d_{100}$ (max) or 1.5 $d_{50}$ (max), and $d_{85}/d_{15}$ = 1.8 to 5.2

$C_3$ = correction for riprap blanket thickness (Figure B2)

$D$ = flow depth, feet

$\gamma_w$ = the specific weight of water, pounds per cubic foot

$\gamma_s$ = the specific weight of the riprap, pounds per cubic foot

$V$ = flow velocity, feet/second

$g$ = gravitational constant, 32.17 ft/sec/sec

The factor of safety ($F_s$) can be adjusted to suit the user or changed for different portions of the structure. A value of 1.2 is recommended for general use. Consideration should be given to increasing the $F_s$ to 1.5 in areas of supercritical flow and hydraulic jumps. The coefficient $C_3$ varies according to the thickness of the riprap blanket as defined by the ratio N of the blanket thickness over the maximum $d_{100}$, which is the maximum size riprap allowed in the gradation. The relation between $C_3$ and the thickness ratio N is shown in Figure B2 for values of N from 1 to 2. ETL 1110-2-120* contains the standard Corps of Engineers riprap gradations.

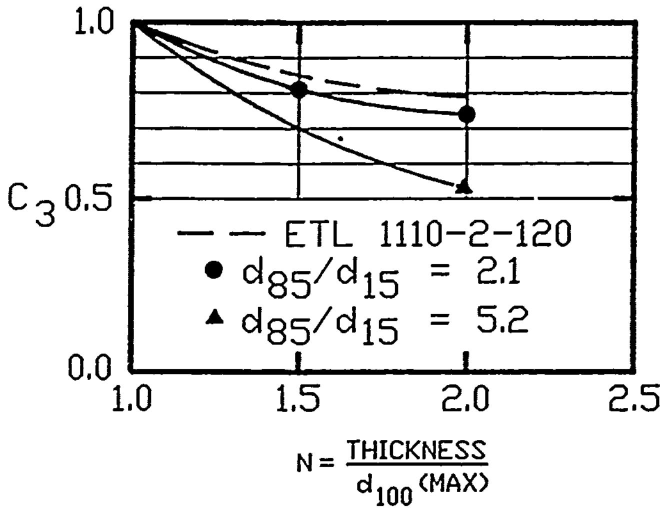


Figure B2: Correction for thickness greater than $1d_{100}$(max) (from Maynord 1987)**

7. If the riprap is stable, the drop structure can be analyzed using a smaller riprap gradation or a thinner riprap layer. If the riprap is not stable, a flatter drop slope, thicker riprap layer, or larger riprap should be analyzed. Although not incorporated in this effort, a code can be written that will compare the computed $d_{30}$ to the selected $d_{30}$ or compute the $F_s$.

8. A smaller riprap gradation can be placed in the downstream end of the exit flare where the velocity decreases. The WASP2 calculations can be used to determine at what point the smaller riprap will be stable. This is done using Equation B2 and solving for velocity knowing the $d_{30}$ of the

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* Headquarters, US Army Corps of Engineers. 1971 (14 May). "Additional Guidance for Riprap Channel Protection," ETL 1110-2-120, US Government Printing Office, Washington, DC.

** Maynord, op. cit.

smaller riprap and assuming a flow depth near channel flow depth. The location of the computed stable velocity for the smaller riprap can then be located on the WASP2 calculations. If a smaller size riprap is placed in the exit flare, WASP2 should be run with the final design to ensure that the total riprap design is stable.

9. The following is a step-by-step description of the above narrative and should be used as a flow chart for designing a type 6 drop structure:

a. Certain basic information is required to begin the design process for the type 6 drop structure. The entering and exiting channel geometry is required and must include the channel slope, the base width of the channel, and the amount of drop to be included in the structure. Basic hydraulic information is also necessary and must include the design flow, design flow depth, and the channel roughness expressed as a Manning's n value.

b. The basic geometry of the drop structure is shown in Figure B1. The initial throat width should be one-third the channel base width.

c. The Manning's n value within the structure should initially be assumed if designing to determine what size riprap is required. If a given riprap gradation and thickness is being analyzed, the Manning's n value can be calculated using Equation B1.

d. A subcritical backwater calculation should be run through the entire structure to determine the water-surface profile and the flow depth and average velocity through the structure. If the calculation can not reach an energy balance at any section, assume critical depth at that section and continue with the calculation.

e. From Step d determine if the water surface at the upstream end of the structure is above or below the design flow depth.

f. Adjust the throat width based on the result of Step e and repeat Step d. If the flow is critical in or downstream of the throat section, the calculation process can be shortened by starting the calculations at the upstream end of the critical flow. When the flow depth at the upstream end of the structure matches the design flow depth (within allowable tolerance) continue with Step g.

g. If a portion of the structure contained critical flow, calculate the water surface and the flow depth and average velocity based on supercritical flow conditions within the same reach.

h. Combine the subcritical and supercritical flow calculations to determine the flow variables through the entire structure. The $F_n$ should not exceed 1.3 entering the tailwater.

i. Using Equation B2 determine the required riprap size and thickness at the calculation points through the structure if a Manning's n value was assumed in Step c. If a riprap gradation and thickness was assumed in Step c, calculate the $F_s$ using Equation B2 at each calculation point.

j. If a Manning's n value was assumed in Step c, decide on a riprap gradation and thickness and repeat Steps c through i. If a riprap gradation was assumed in Step c and the $F_s$ is not satisfactory from Step i, repeat Steps c through i, using another riprap gradation or thickness. Once the $F_s$ is satisfactory, continue with Step k.

k. Evaluate the exit transition to determine if a smaller riprap gradation or thinner blanket can be placed in the downstream portion of the exit based on lower average velocities. If a smaller riprap gradation is used, repeat Steps c through j to develop the final design and flow variables.